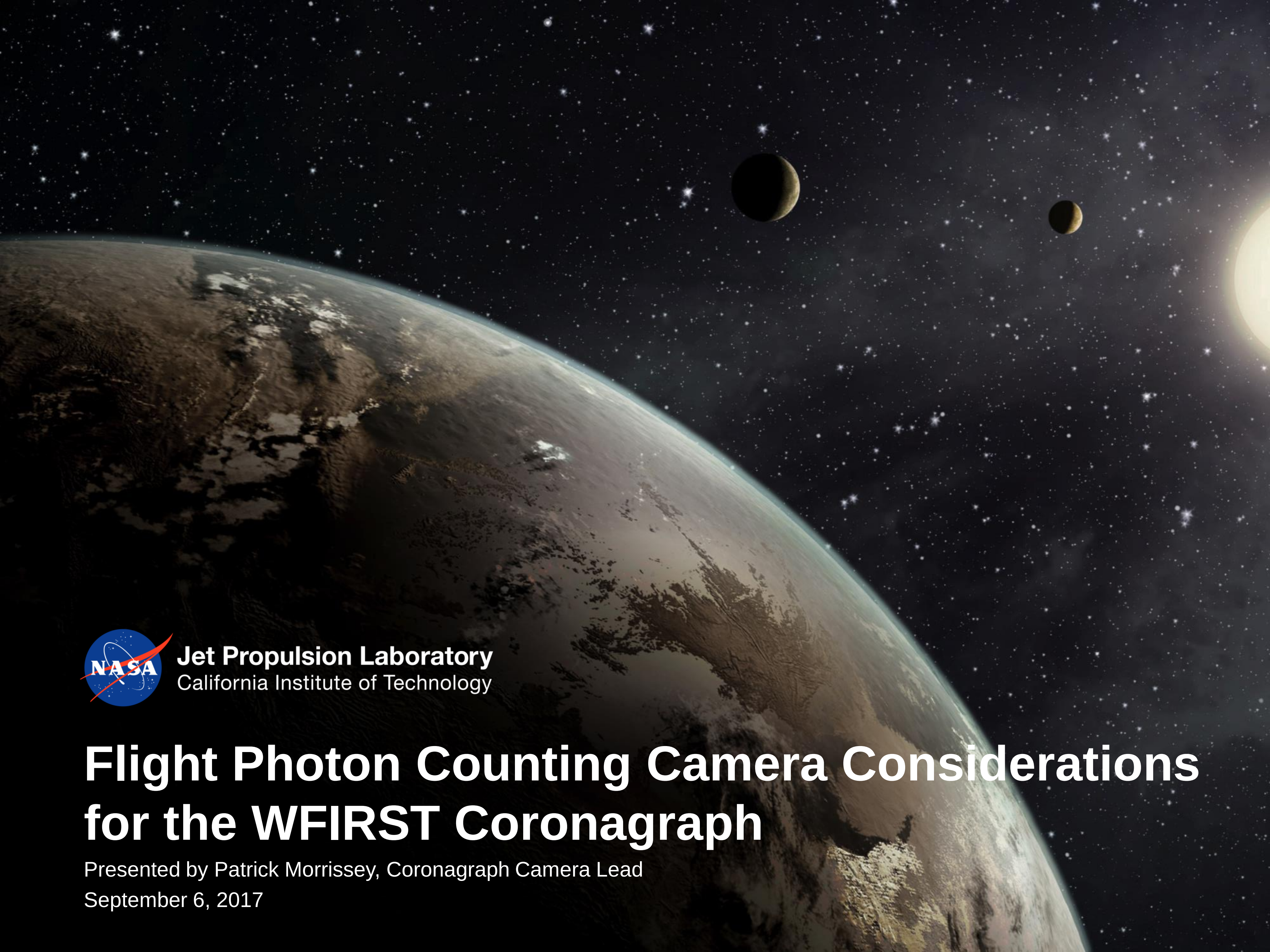

Jet Propulsion Laboratory
California Institute of Technology

Flight Photon Counting Camera Considerations for the WFIRST Coronagraph

Presented by Patrick Morrissey, Coronagraph Camera Lead

September 6, 2017

WFIRST Coronagraph Camera Team

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Coronagraph Flight Considerations Outline

- Mission and Science Overview
- Coronagraph Description
- Requirements and EMCCD Performance
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- The LOWFS Wavefront Sensing Mode
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WFIRST

WIDE-FIELD INFRARED SURVEY TELESCOPE

DARK ENERGY • EXOPLANETS • ASTROPHYSICS

Science Objectives

Jet Propulsion Laboratory
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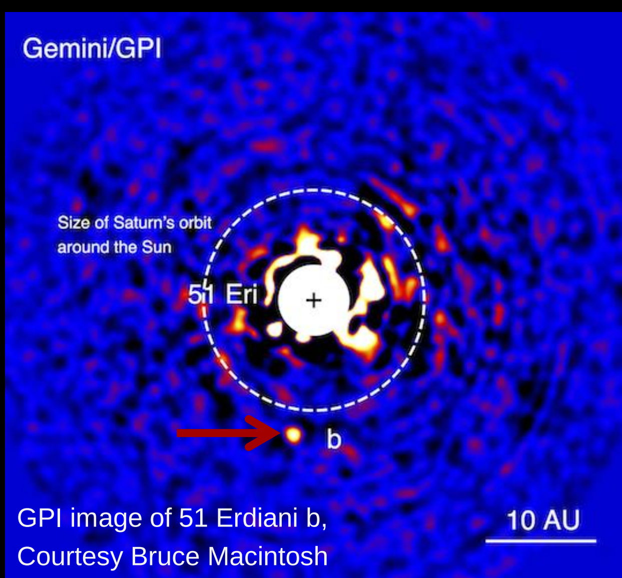
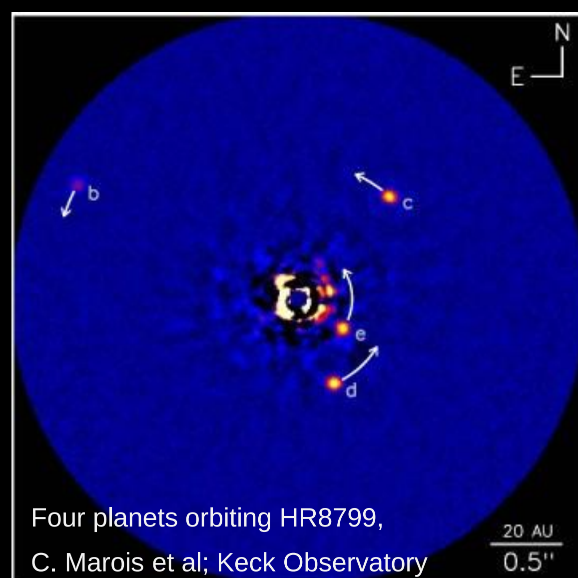
DARE MIGHTY THINGS

- **WFIRST is the Wide Field Infrared Survey Telescope, a major new NASA observatory set to fly in the mid 20s. Its prime science mission is to study supernovae and gravitational (weak and micro) lensing**
- **WFIRST will also fly a Coronagraph Instrument designed to make direct images and spectra of planets around nearby stars**
- **The coronagraph is a *technology demonstration mission* that will showcase precision pointing, active wavefront control, and optical photon counting detectors in space for the first time.**



GPI image of 51 Erdiani b,
Courtesy Bruce Macintosh



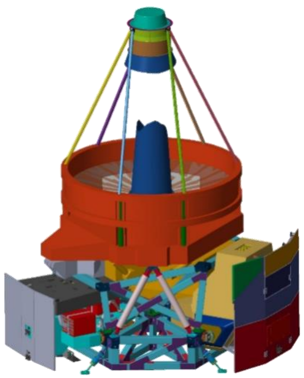
Four planets orbiting HR8799,
C. Marois et al; Keck Observatory

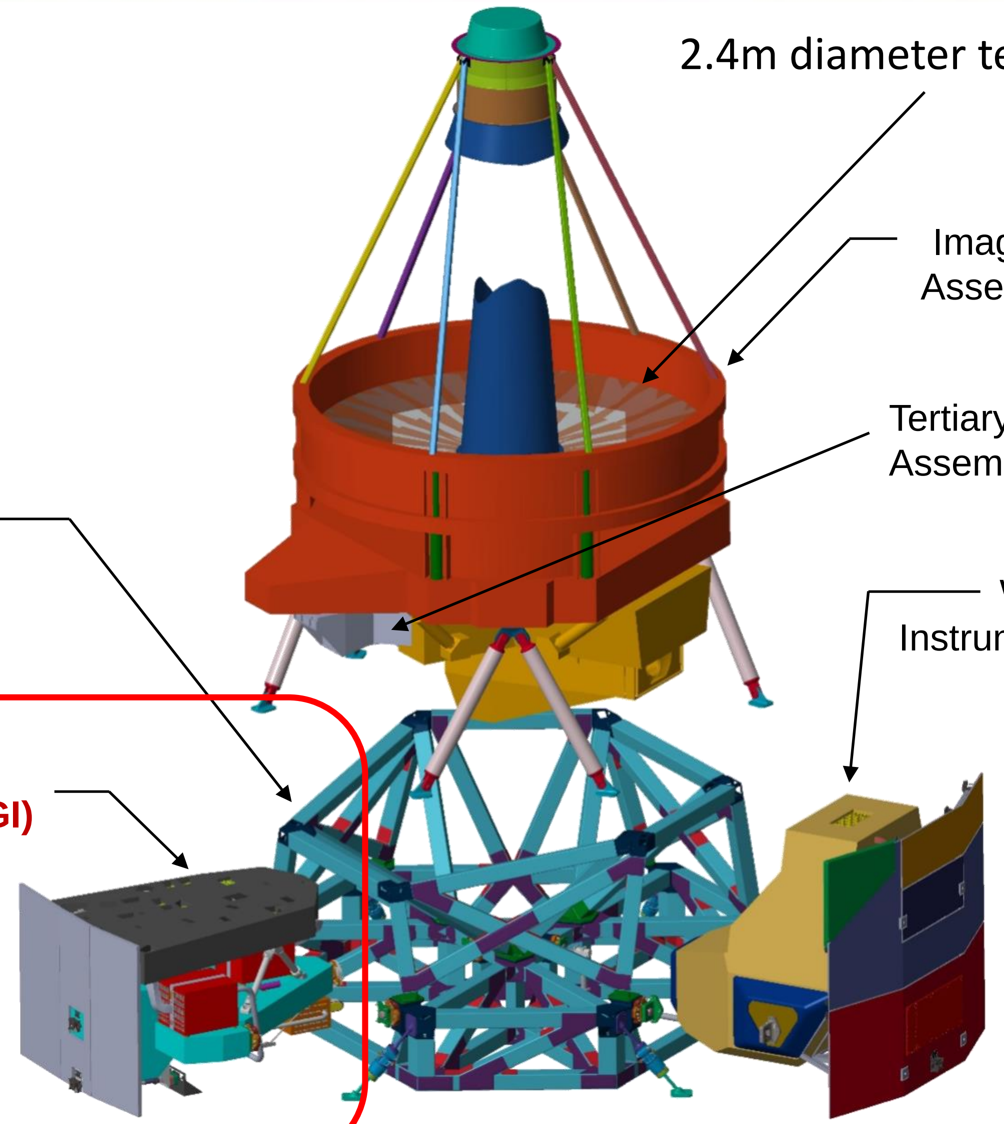
The exciting field of exoplanet discovery and characterization is successfully identifying many new planetary systems. Most are too far to be directly imaged.

The few that have been directly imaged from the ground contain large, self-luminous planets.

The WFIRST CGI will make the first images of planets that are similar to the ones in our own solar system.

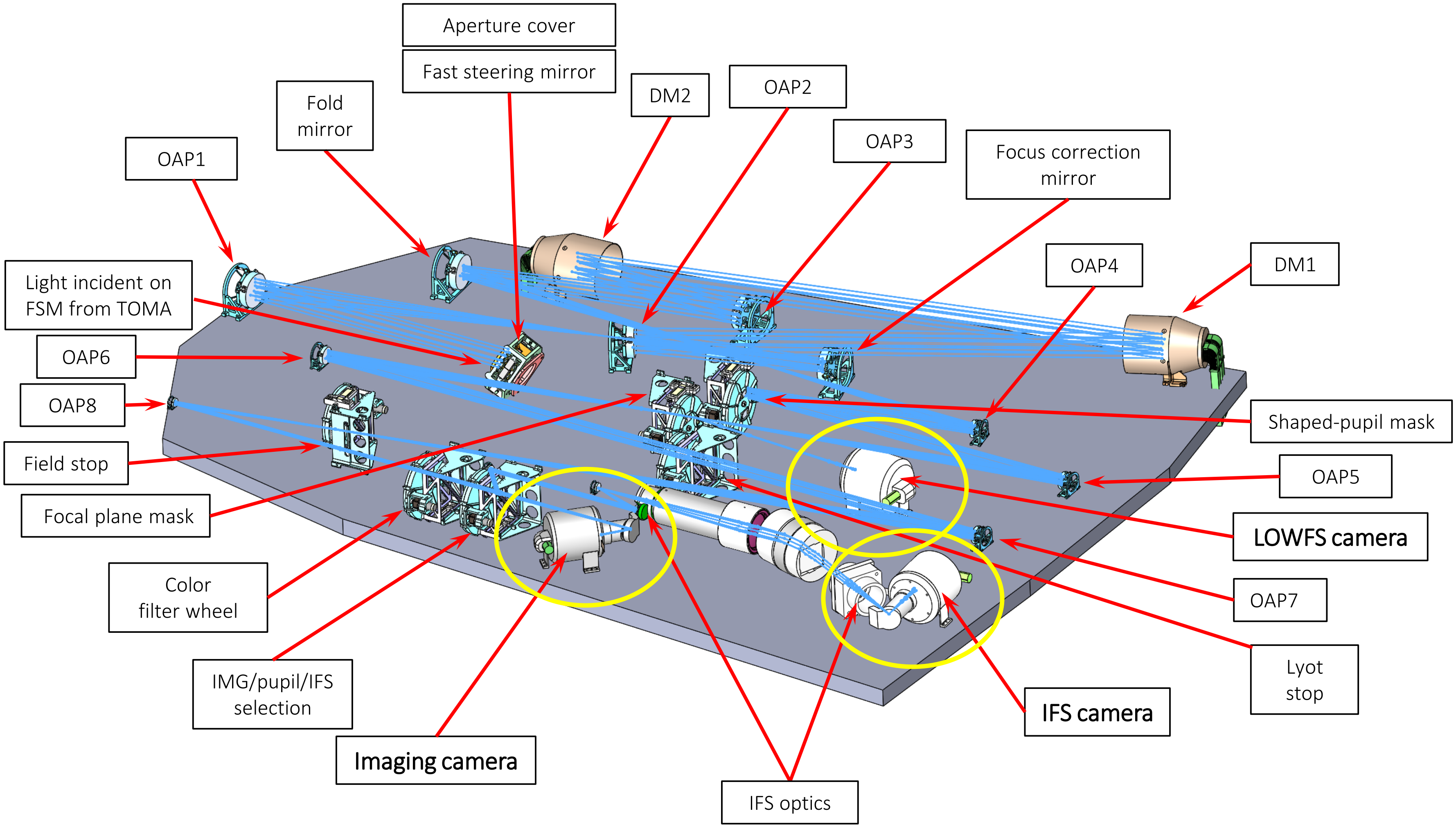
CGI in WFIRST Payload


Payload, integrated

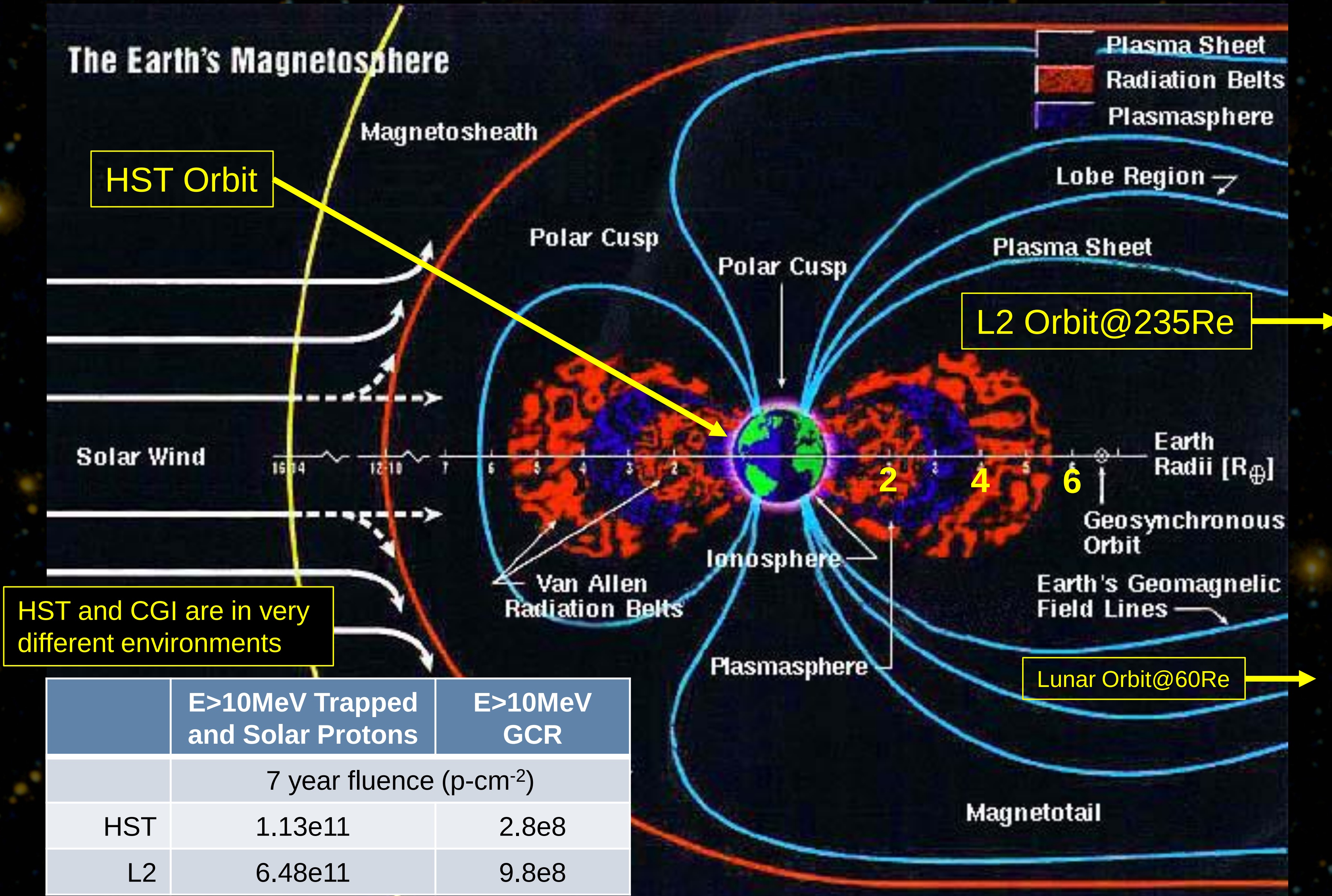


Payload, exploded view

Coronagraph Layout



LEO vs L2



	E>10MeV Trapped and Solar Protons	E>10MeV GCR
	7 year fluence (p-cm^{-2})	
HST	1.13e11	2.8e8
L2	6.48e11	9.8e8

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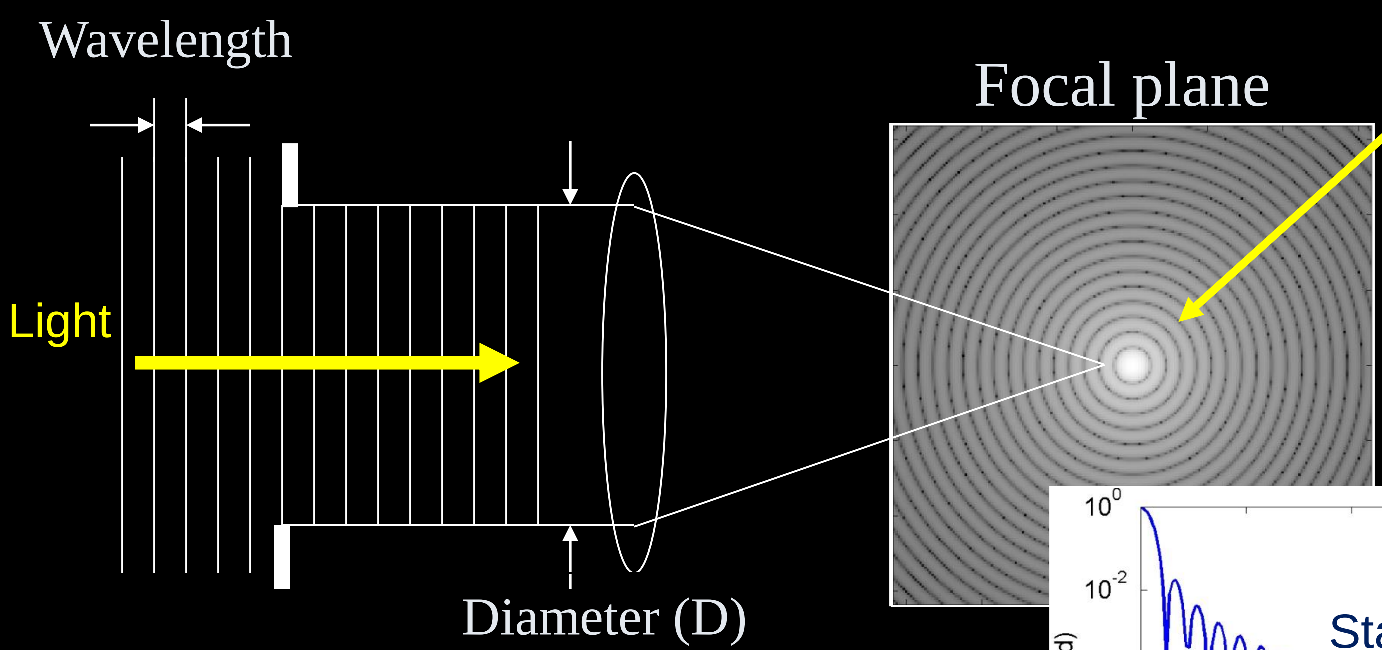
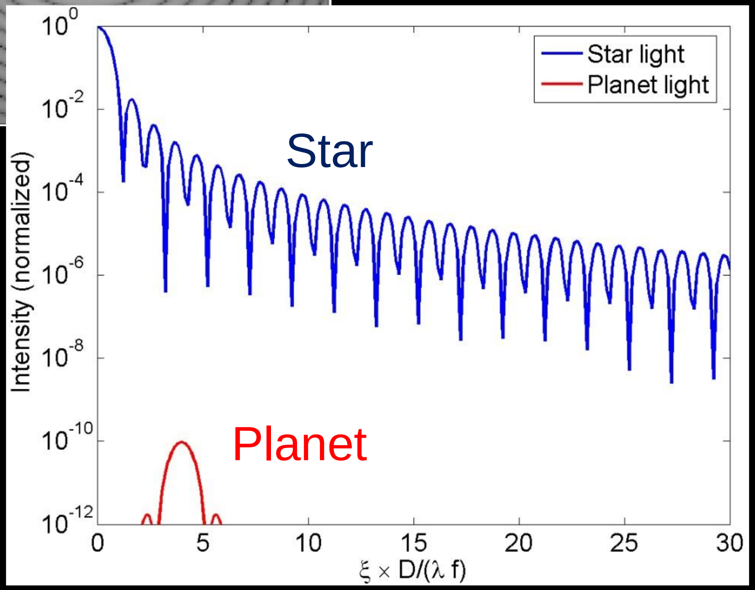
Diffraction



The planet is hidden in here, and would be over a million times dimmer)



Diffraction is a big problem for direct exoplanet detection.

- Bigger telescopes help
- Coronagraphs suppress the diffraction

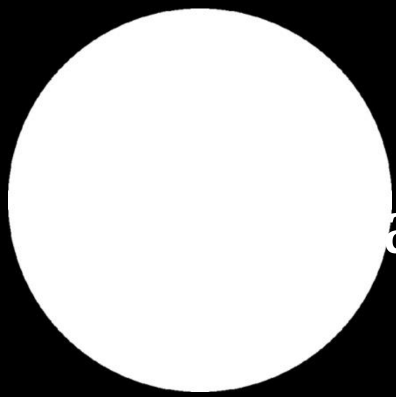
The Lyot Coronagraph

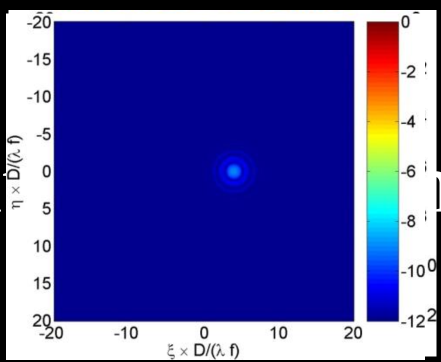
Entrance pupil

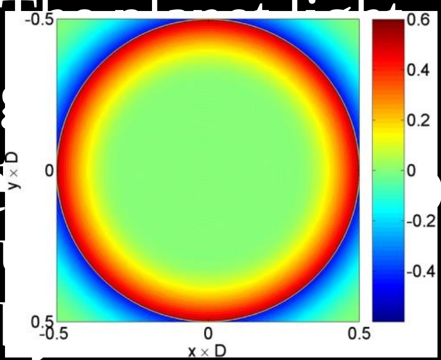
Occulter

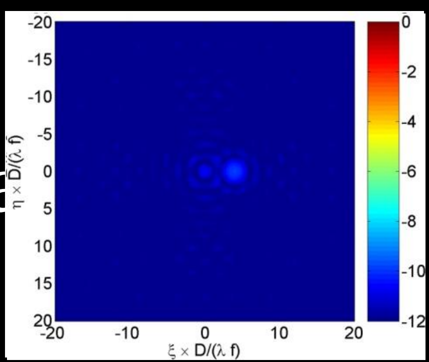
Lyot stop

Image plane









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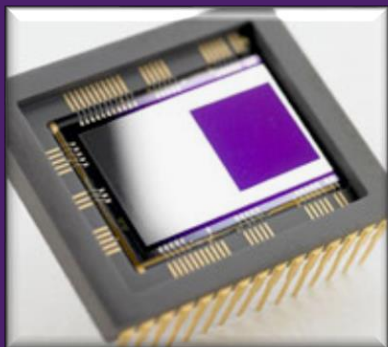
Detector Requirements

- Science
  - Planets are small and even if the diffraction problem is completely solved, they present a small surface area to reflect starlight.
  - Predicted exposure times are of order *days*
  - In order to extract the science signal, the detector must have:
    - High visible-light QE (>75%) to both minimize diffraction and detect methane absorption bands.
    - Minimum noise, since in many cases (including the most important ones) the observations will be detector-noise limited.
    - Large format to capture many lenslet spectra (>1Kx1K)
- Wavefront Control
  - Fast frame rate (1000 fps)
  - Low Latency
  - Low noise (<5e$^-$)

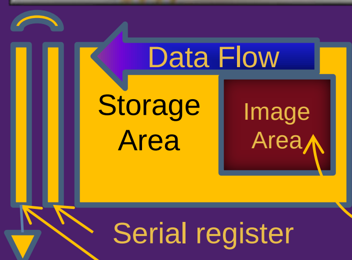
Both objectives can be addressed with the Teledyne-e2v Electron Multiplying CCD (EMCCD)

The Electron Multiplying CCD Concept

e2v L3 Technology



- New technology from e2v enables high QE CCD imaging and **zero read noise** photon counting.
- A **Low Light Level (L3) extended serial register** operating at elevated voltage (~50V) amplifies signals well above the level of the read noise.



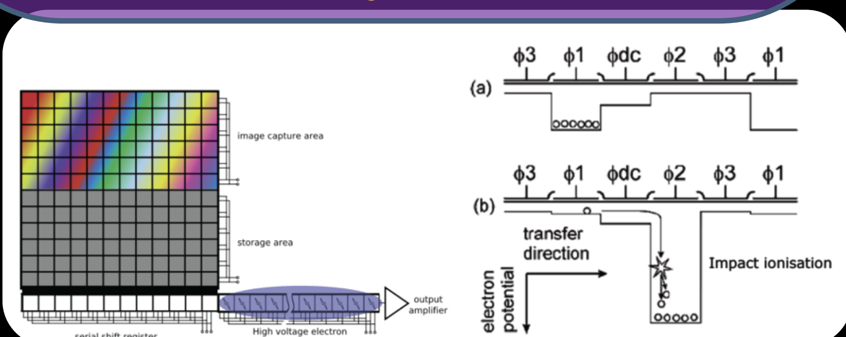
L3 functional diagram

Serial register

Photon input

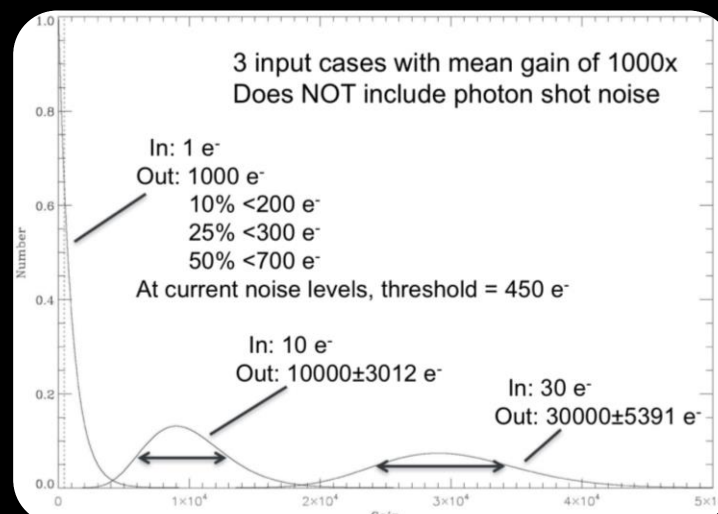
Extended serial register (50V)

Amplified data is sent to a photon counting discriminator, eliminating read noise.



Three modes of operation:

1. Unity gain: just like a conventional CCD
2. Moderate gain (<1000x): The so-called **"analog mode"** reduces the effective read noise by 1/gain but adds an effective QE penalty
3. High gain (>1000x): This is the **photon counting mode** and eliminates the QE penalty.



Photon Counting Yields Best Performance

Limiting noise is shown in RED.

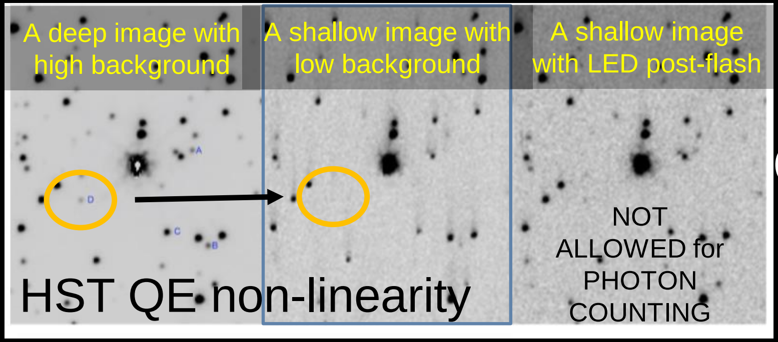
	Long Frames	Short Frames	
Mode	EM Analog	EM Analog	Photon Counting
Effective QE	0.45	0.45	0.75
Total Exposure	100000 s		
Frame Time	2000 s	20 s	20 s
Frames	50	5000	5000
Read Noise (90e-)	±1.3 e^-	±13 e^-	0 e^-
*CIC (3e-3 e^--px^{-1}-fr^{-1})	0.15 e^-	15±3.9 e^-	15±3.9 e^-
Dark Current (2 e^--px^{-1}-hr^{-1})	55±7.4 e^-	55±7.4 e^-	55±7.4 e^-
Gain	500	1000	1000
Detection Limit (5σ)	CR-limited	77 e^-	42 e^-

1. Frame times may be limited by cosmic ray tails to ≲100s.
2. CIC effectively sets a dark current floor of 0.2-0.4 e^--px^{-1}-hr^{-1}, so it is important to minimize as much as possible

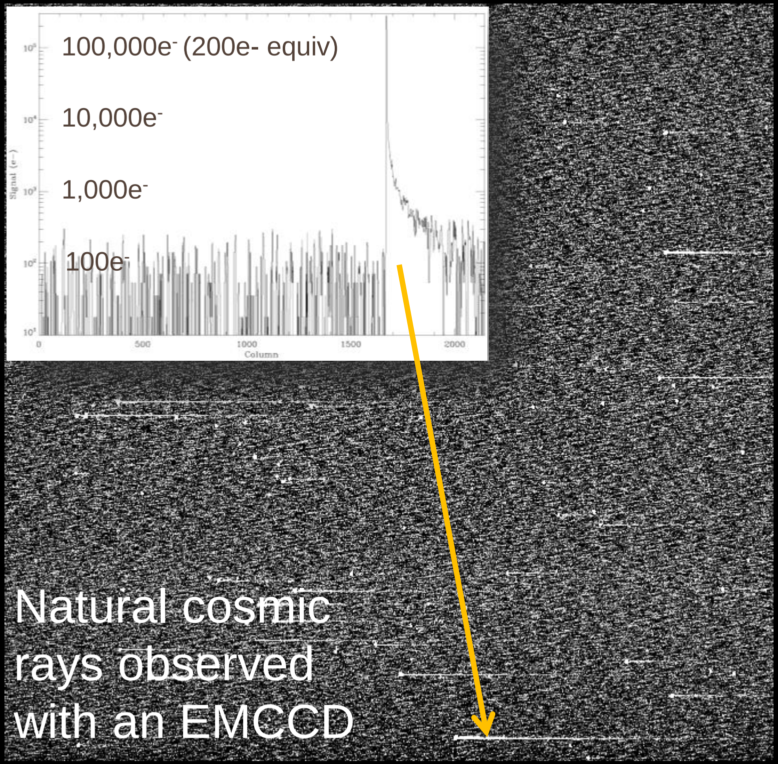
The EMCCD Path to Flight

There are three main areas we are addressing to prepare for our flight application:

1. **Radiation Damage:** All CCDs are sensitive to radiation to varying degrees. Radiation damage causes hot pixels and also degrades charge transfer efficiency, introducing a QE non-linearity at very low fluxes (such as are required for exoplanet astronomy)
2. **Cosmic Ray Contamination:** Bright cosmic detections will occur at ~**300x** the typical ground rate at L2 orbit. Cosmic rays saturate in the EMCCD gain register and leave a long tail.
3. **Packaging:** The commercial EMCCD package must be adapted for a flight application and meet requirements (flatness).



(1)



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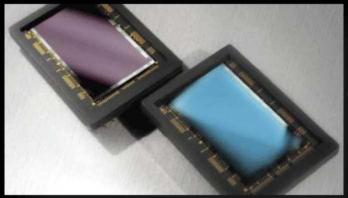

(3)

Commercial EMCCD package

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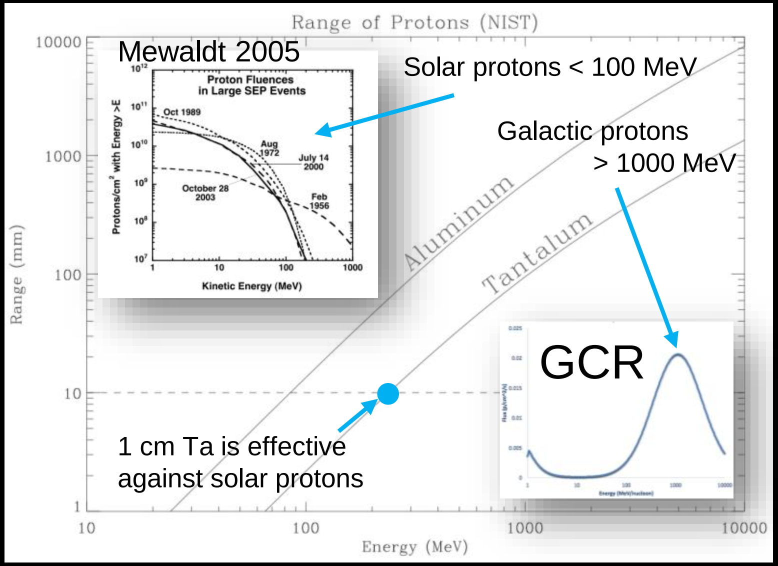
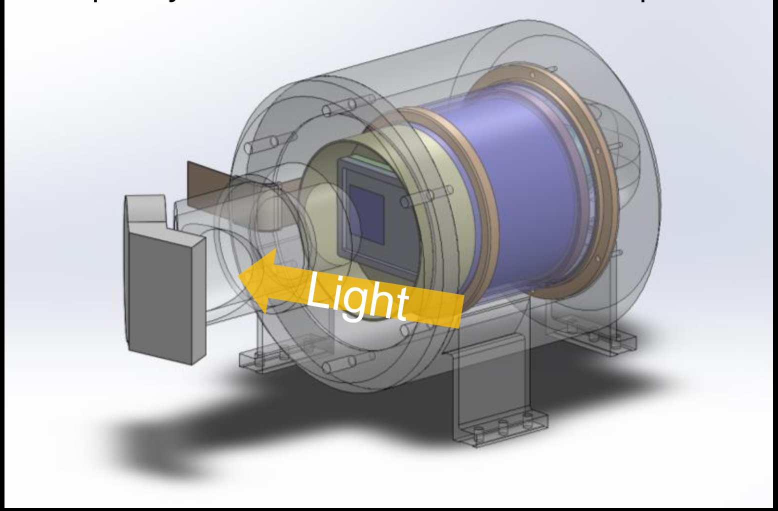
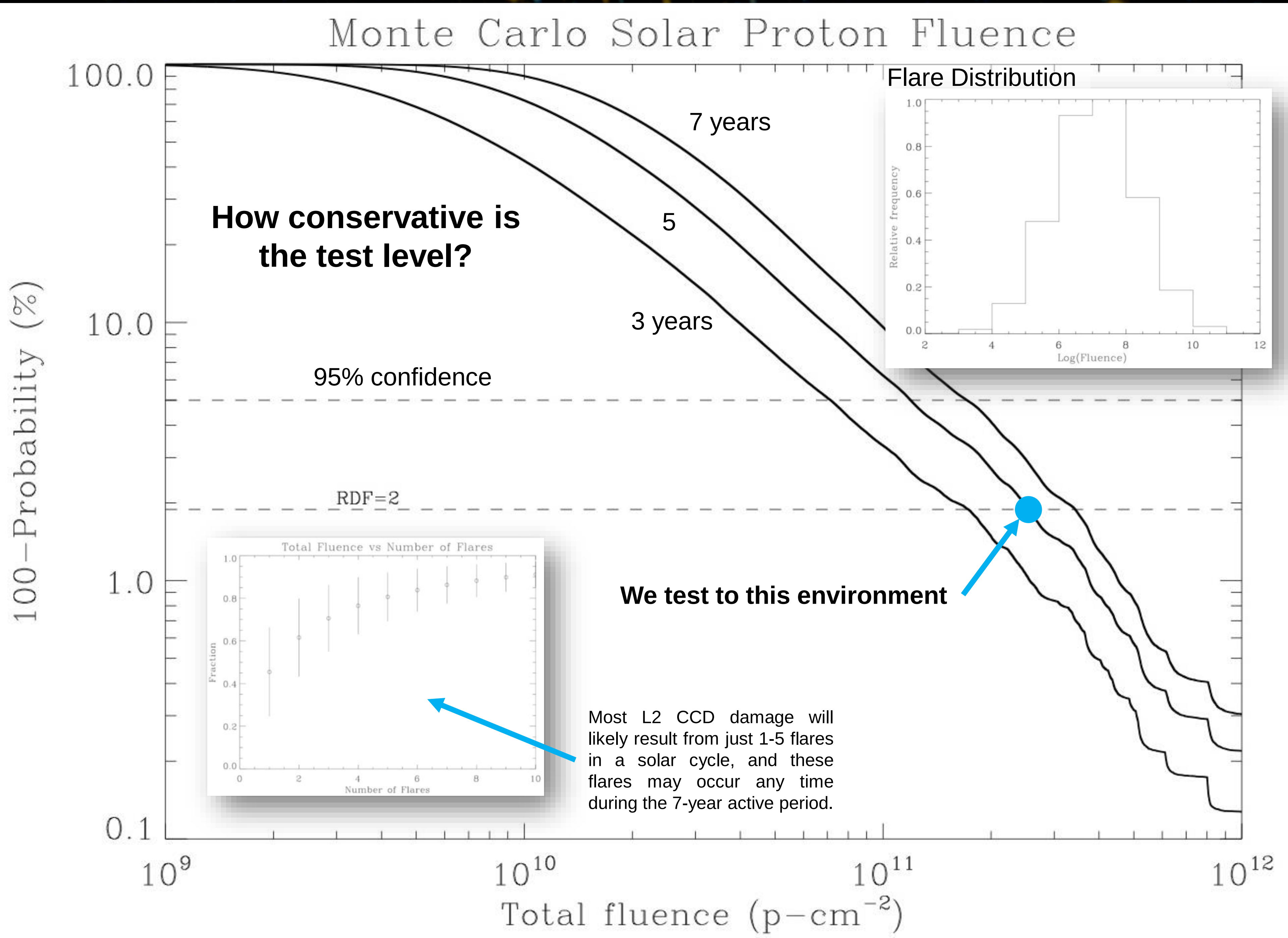
The CGI Environment and Shield Design

1. **Radiation Environment:** The WFIRST CGI will be at L2, outside the protection of Earth's magnetic field. The radiation displacement damage dose (DDD) will primarily be in the form of protons from sporadic solar flares. This radiation is primarily <100 MeV and can be effectively shielded. There is also a Galactic component that is much more energetic and can not be shielded.
2. A shield concept has been developed that fully encloses the EMCCD. There is no direct view with <1cm Ta. Since protons travel mainly in straight paths and there are few electrons to scatter, this is an effective shield.
3. The total model dose inside the shield is about 1.3×10^{9} p-cm^{-2} 10 MeV equivalent. The Total Ionizing Dose (TID) is expected to be < 1 krad.



Completely enclosed, 1cm Ta Shield Concept



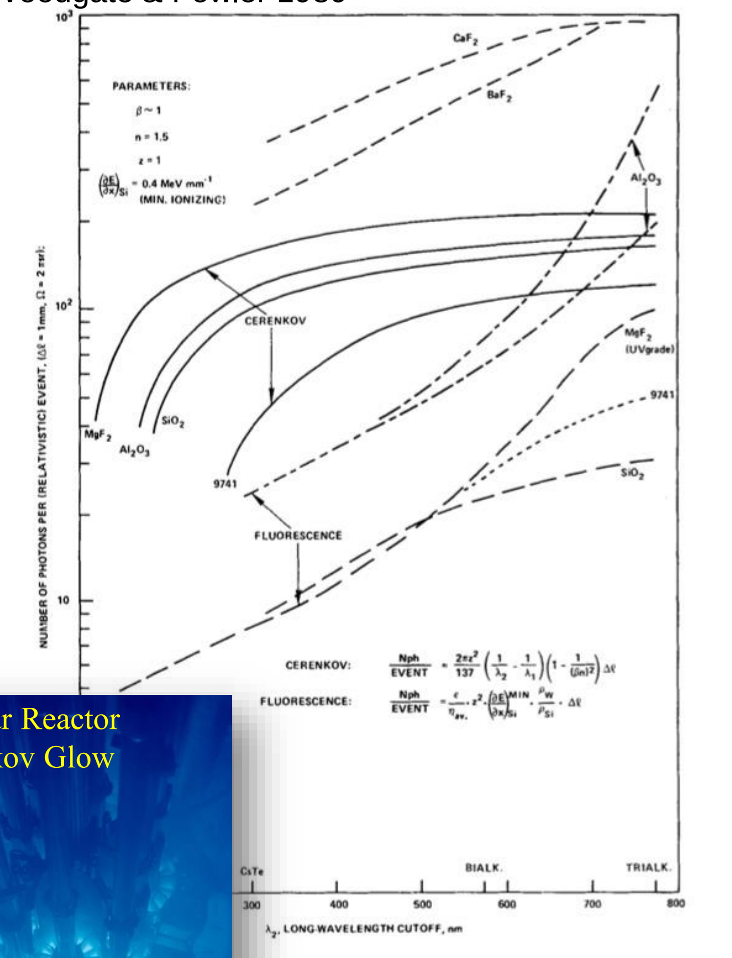


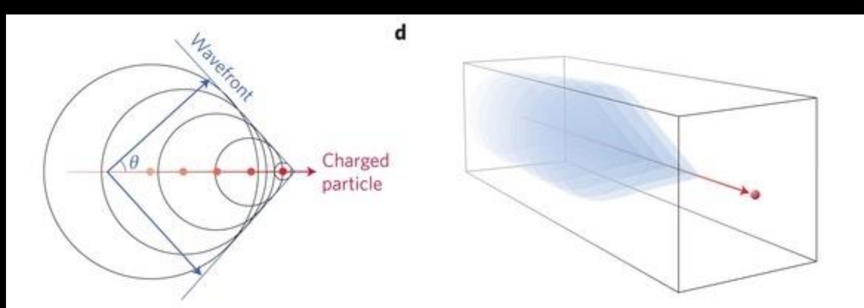
Most L2 CCD damage will likely result from just 1-5 flares in a solar cycle, and these flares may occur any time during the 7-year active period.

Secondary Radiation Considerations

- Energetic particles (GCR) moving faster than the speed of light in the medium will radiate broad spectrum Cerenkov light
  - Depending on the sensitive band of the detector, there could be 10s to hundreds of photons per particle event (5 protons-s^{-1}-cm^{-2} GCR)
- The same energetic particles will ionize the glass as they pass through, leading to a fluorescent light pulse ~1 μs later.
  - The size of the pulse depends on the type of material. The fluorescent light is also broad spectrum. CaF_2 appears to be a bad actor.
  - Long time constant emission (phosphorescence) is also possible.
- REQUIREMENT: No optics in close proximity to the EMCCD. Screening of elements as necessary for phosphorescence.

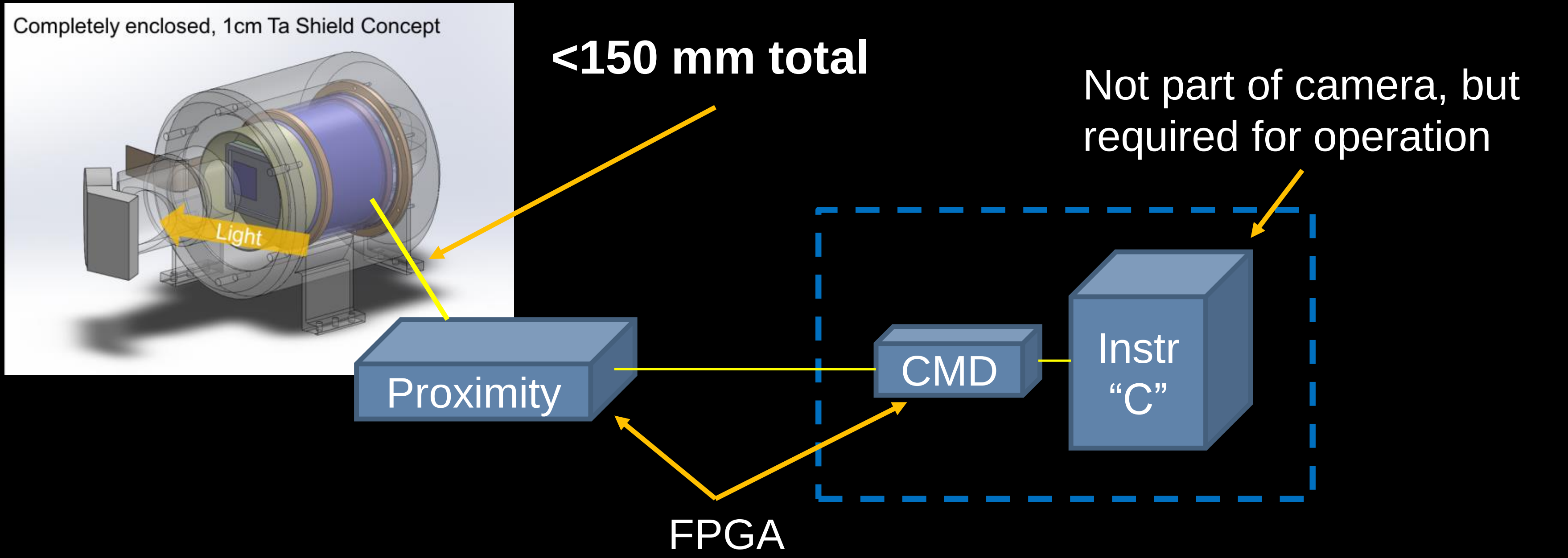
Woodgate & Fowler 1989





CGI Camera Deliveries (2021-22)

- Science Cameras:
  - EM Camera + EM electronics held for testing
  - 2 FLT Cameras + FLT Electronics -> I&T
- LOWFS Camera:
  - EM LOWFS Assembly + EM electronics to Testbed
  - 1 FLT Camera + FLT Electronics -> I&T



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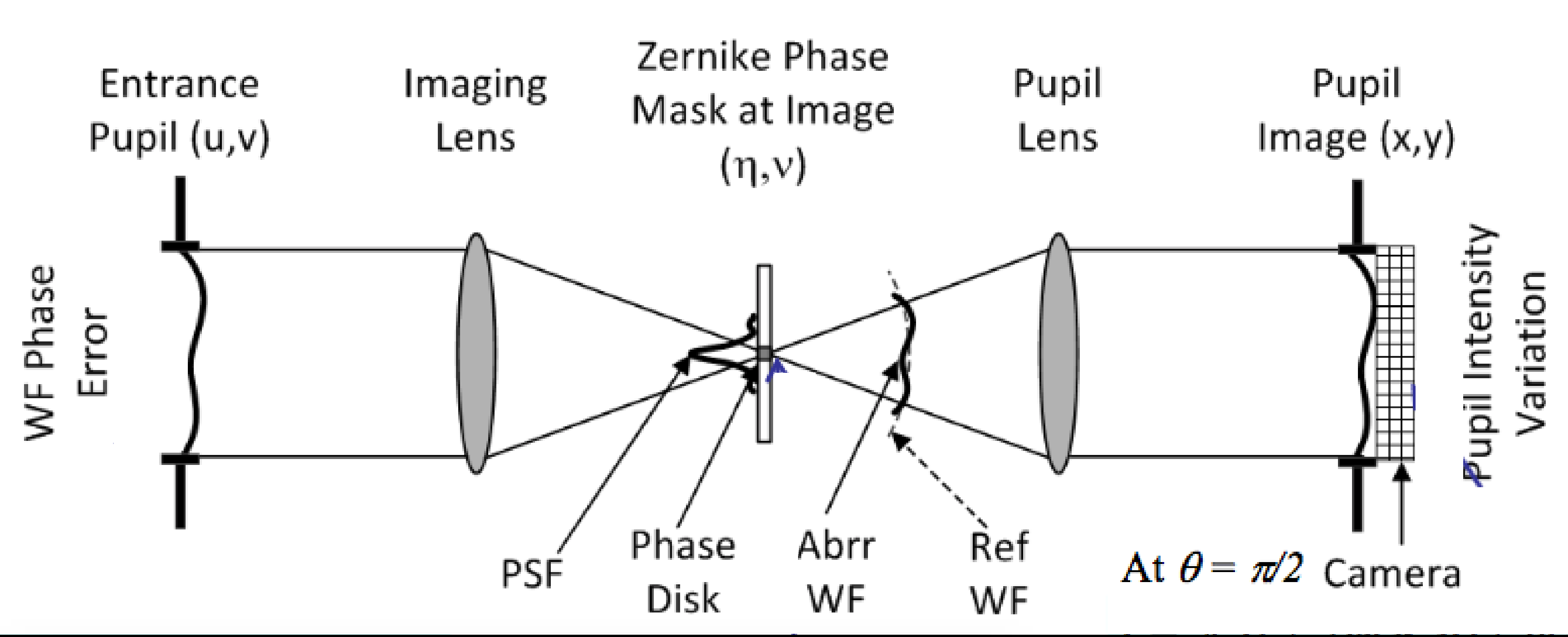
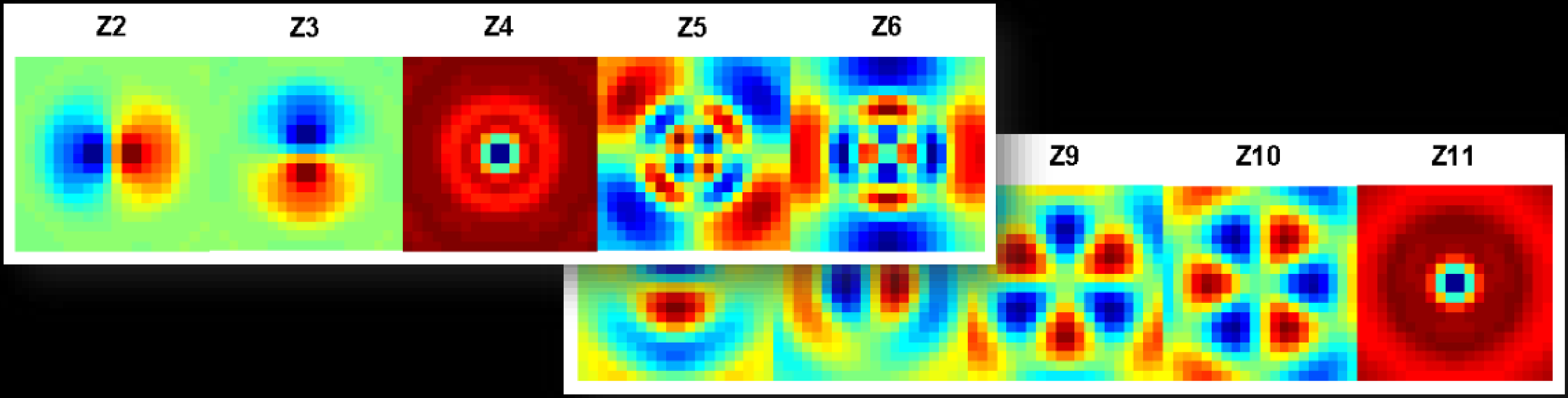
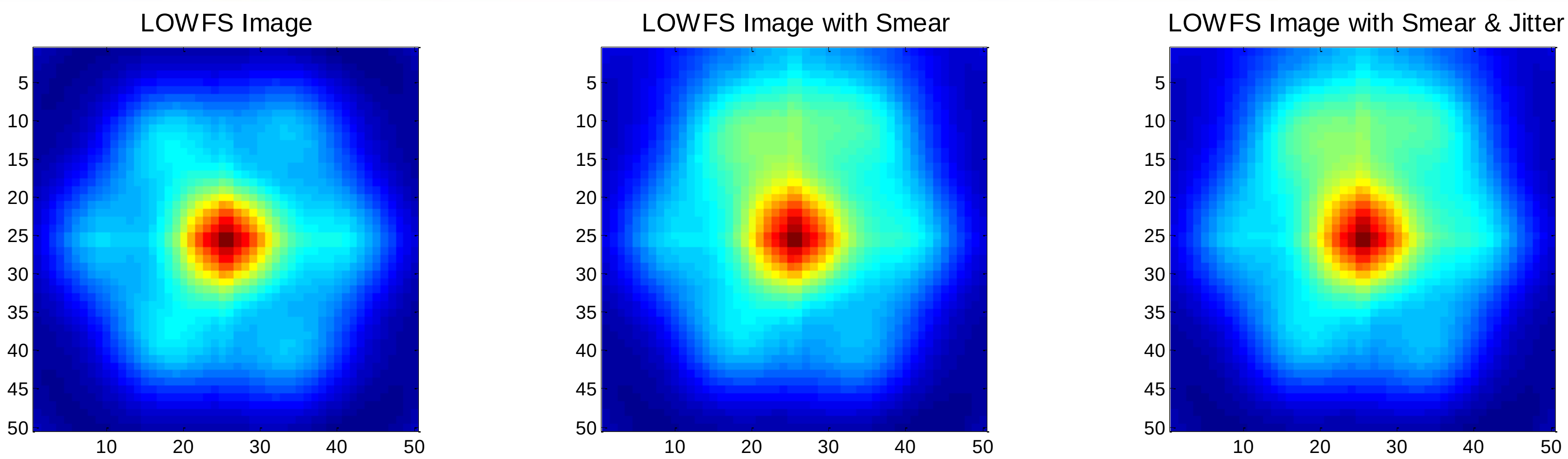
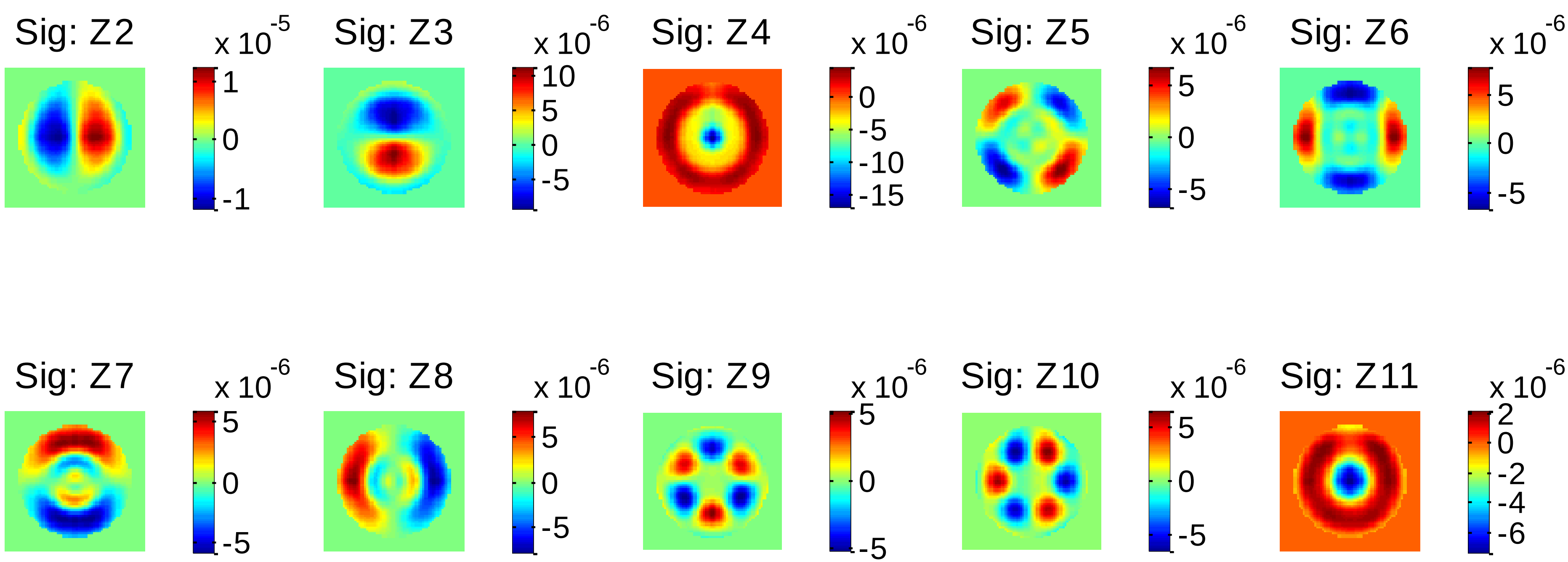
WFIRST CGI LOWFS Overview



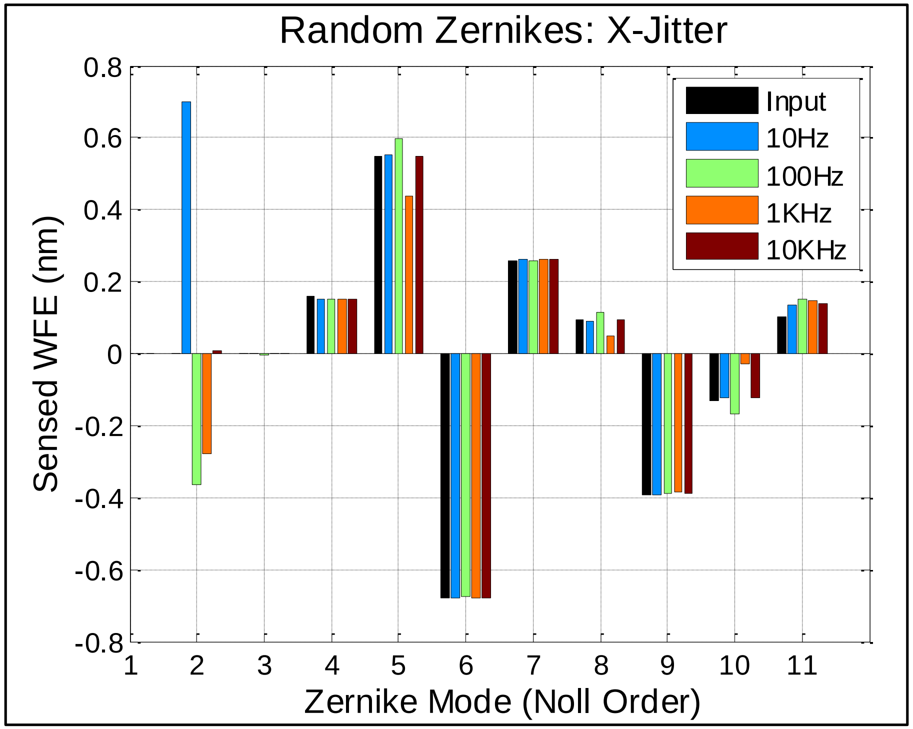


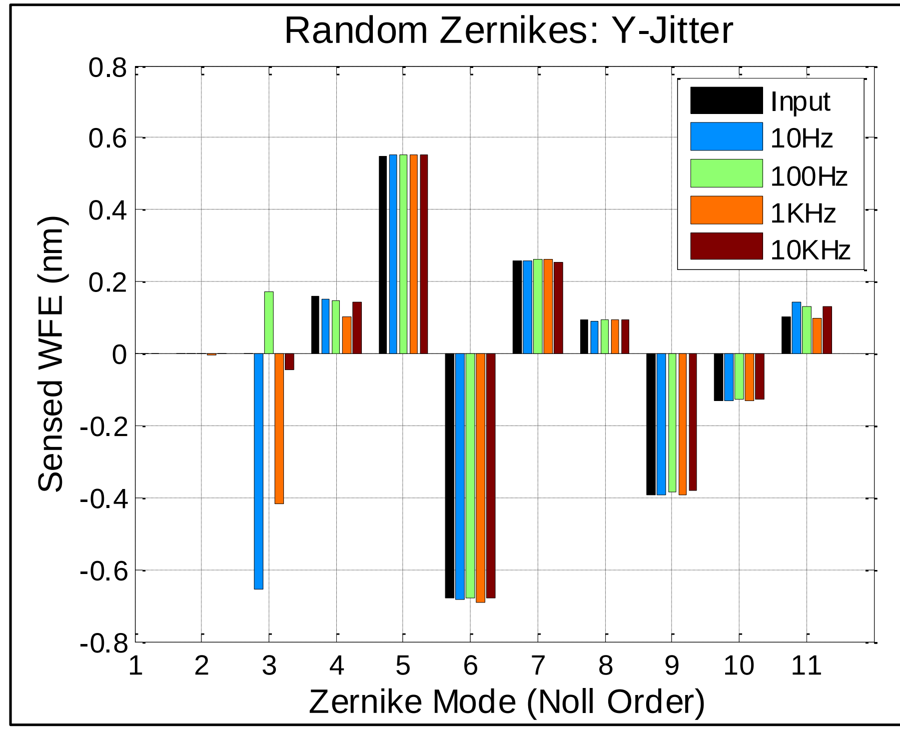
LOWFS Images and Reconstructor Base using Smeared Image





LOWFS Signal Extraction Models with Shutterless EMCCD





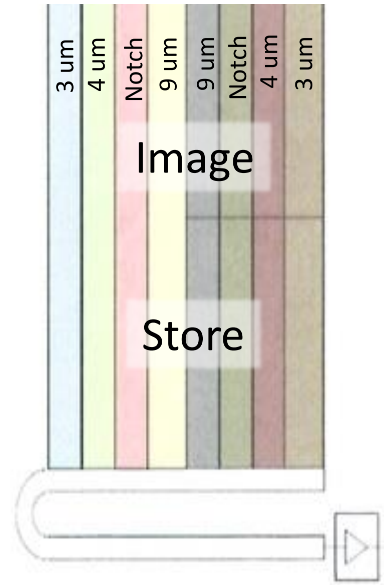
- Input LOWFS image composed from random Zernike terms (black bars)
- The other bars are from various jitter frequencies
- Left plot is with X jitters and right is with Y jitters

Engineering Improvements Now in Production

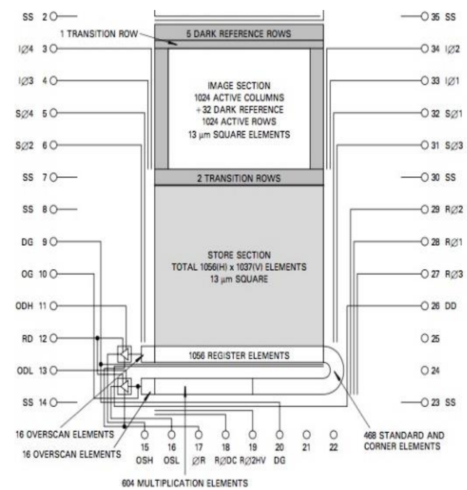
Jet Propulsion Laboratory
California Institute of Technology

- We have contracted Teledyne-e2v to implement some simple modifications to the commercial EMCCD CCD201-20 that are expected to improve charge transfer at low flux.
  - The changes **1) narrow the path that small charge packets follow** when being read from the CCD image pixels.
    - Similar designs produced by e2v have flown on Hubble Space Telescope instruments (for example, WFC3).
    - Several narrow channel designs are being tested and are expected to improve the charge transfer degradation at low flux by ~2× or more.
  - We will also **2) remove the store shield** to eliminate unnecessary charge transfer, **3) improve the output amplifier** to reduce the required device gain and **4) add a gain register overspill** to address the nuisance cosmic ray tail problem.
- The first set of devices with the store shield removed will be delivered **December 2017**.
- The second set of devices with narrow image channels and improved amplifier will be delivered **October 2018.**
- **Improvements could enhance dQE performance ~2× at our fiducial planet flux and more at fainter flux levels**.

Test Design



Commercial Design



Summary

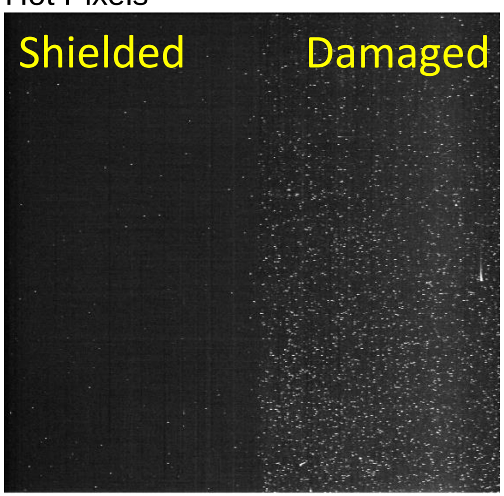
- The WFIRST Coronagraph Instrument represents an exciting opportunity for technology development and exoplanet science in the coming decade.
  - First adaptive optics system in space
  - First use of optical EMCCD photon counter in space
- The EMCCD offers the best performance possible for visible/red photon detection with ultra low noise
- A radiation test program has evaluated the performance of the commercial version of the device (next talk: Harding et al.)
- A technology program is underway to make improvements. Planned developments will address:
  - Charge transfer of small signal packets
  - Control of cosmic rays in the serial register
  - Flight quality packaging
- Results to come in 2018!

Backup

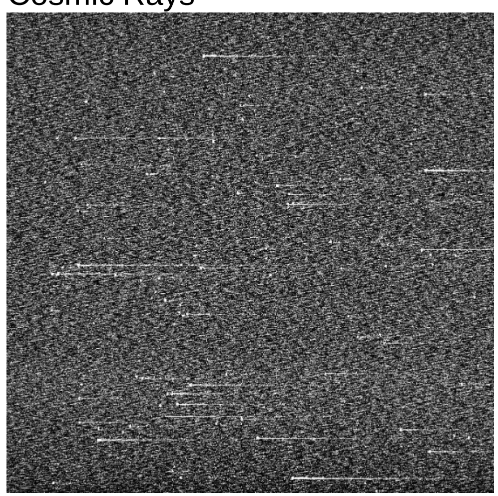
Radiation Test Results

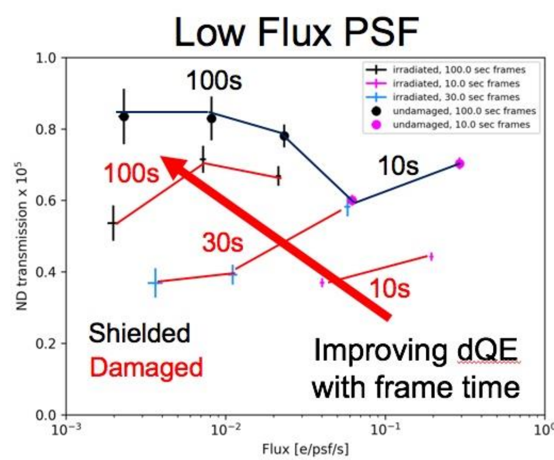
- Proton damage manifests itself in the form of 1) hot pixels and 2) charge transfer degradation.
  1. **Hot pixels** may have much higher dark than the typical pixel (>10×); however, these pixels are ~10% of the total, even at end of mission.
     - The *diffuse* dark current remains under 1 c-px^{-1}-hour^{-1} (very low).
  2. **Charge transfer degradation** disproportionately affects faint signals since traps are efficient when they are empty.
     - *Increasing the frame length is an effective mitigation but is limited by the long tails of cosmic rays generated in the EM gain register.*
- The radiation-damaged detector performance at 5 years meets the requirements of SE. Improvements that can increase project margin are now being implemented in the sensor design at Teledyne-e2v, similar to previously flown concepts (cf. HST WFC3).

Hot Pixels



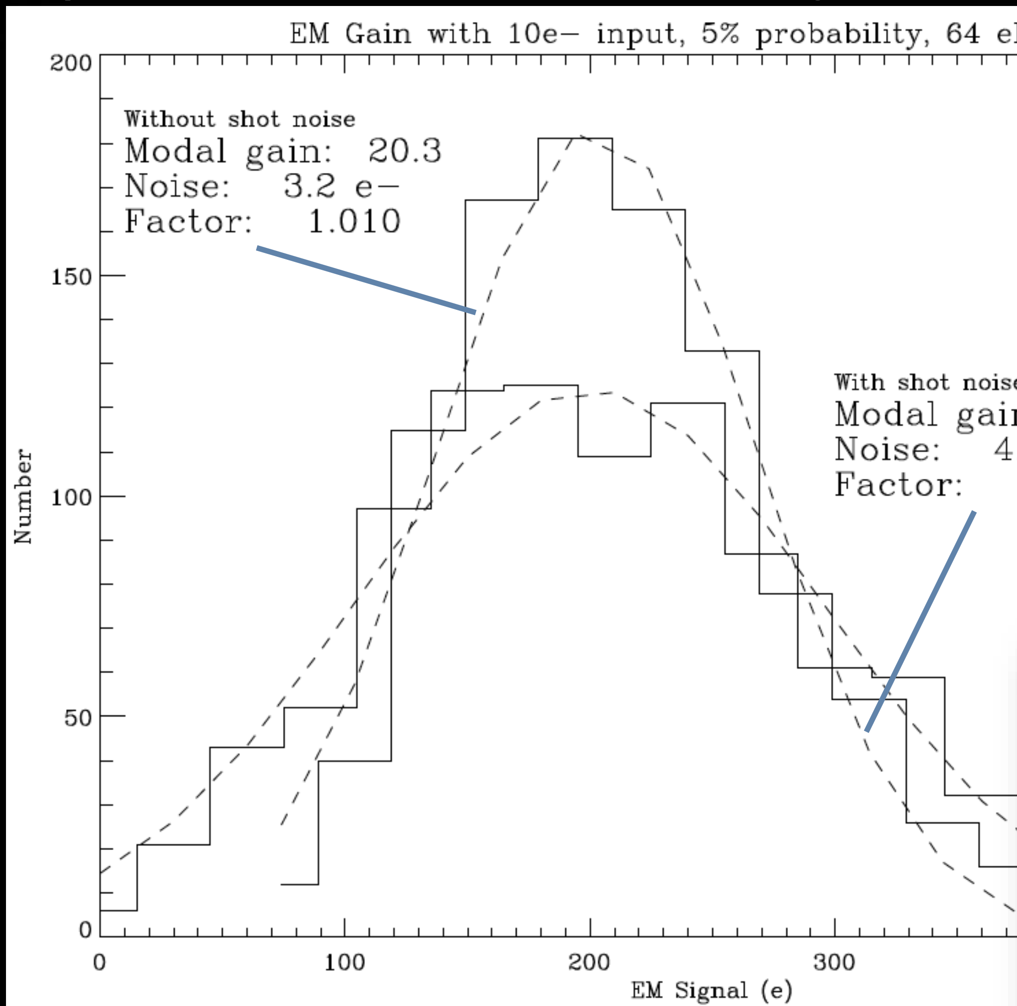
Cosmic Rays

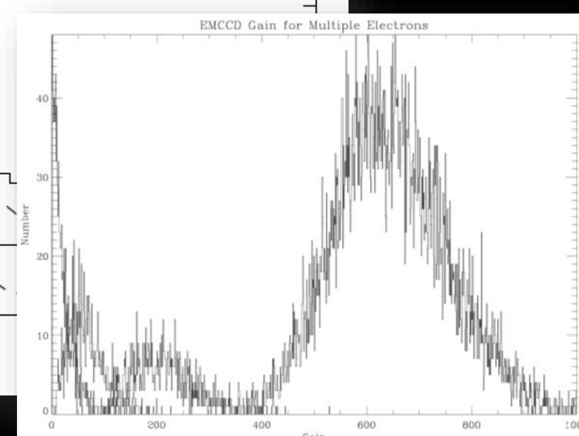


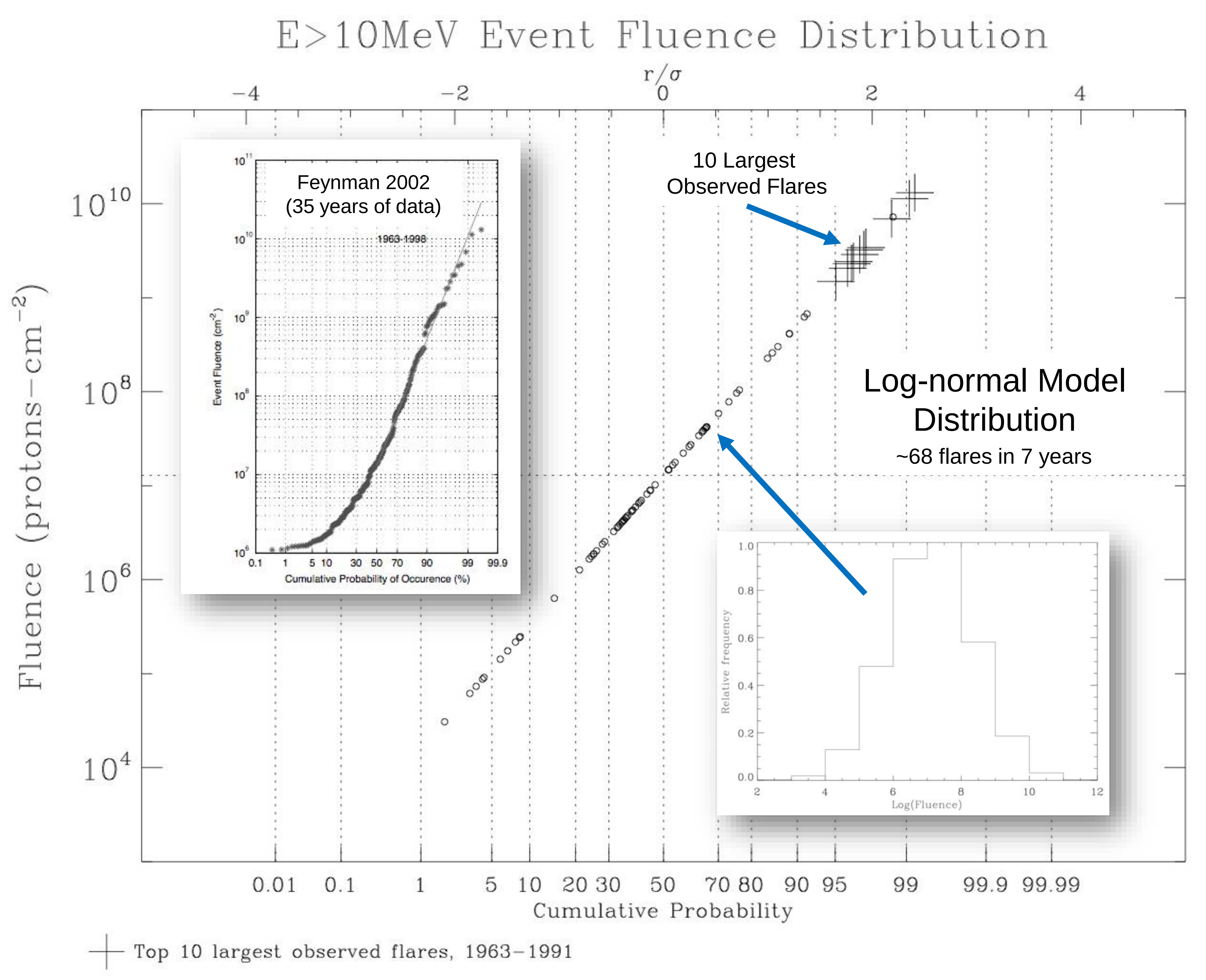


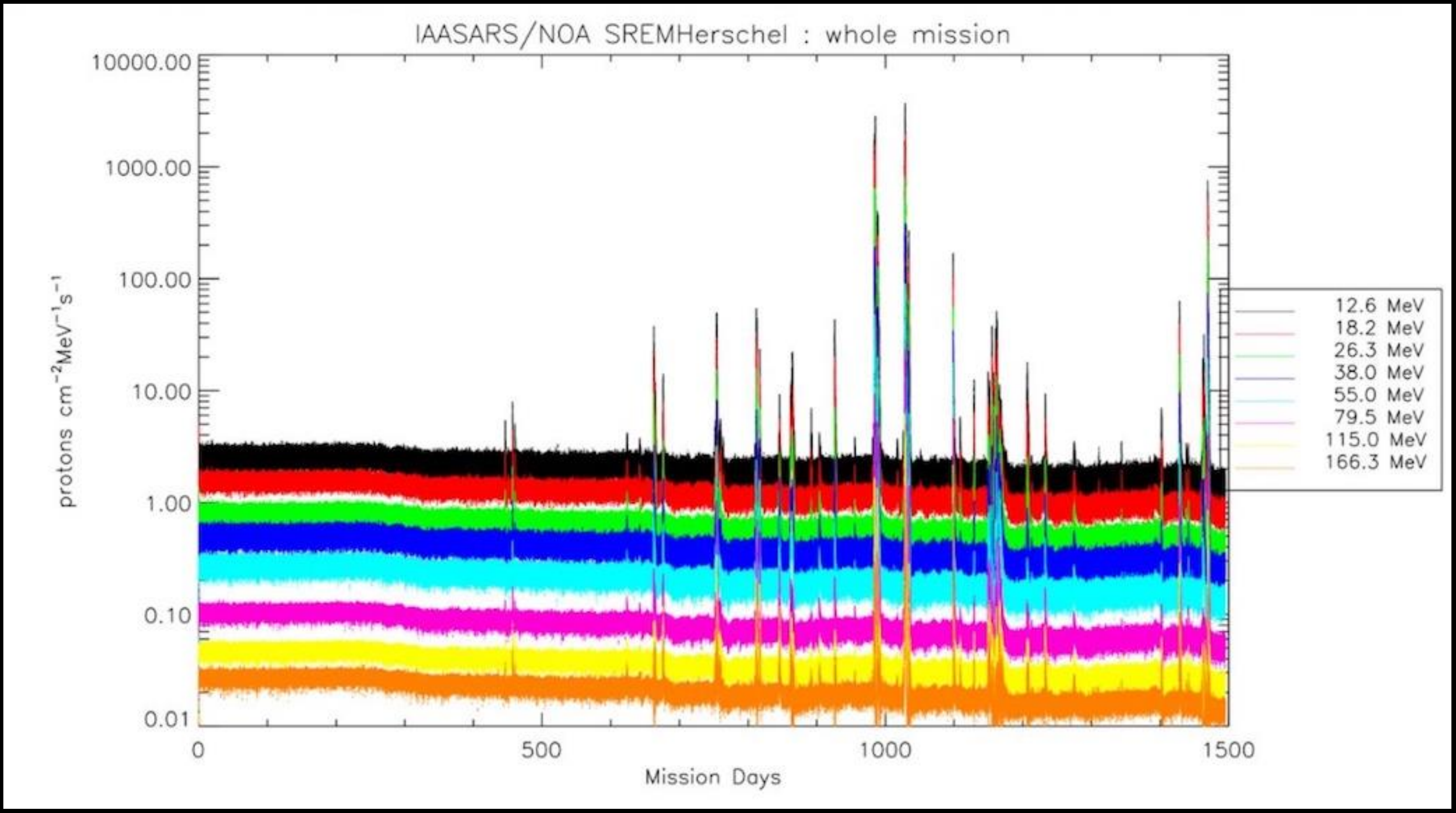
EMCCD Gain Register Noise

with photon shot noise broadening






E>10MeV Event Fluence Distribution
r/σ
−4
−2
0
2
4
10^{10}
10^{8}
10^{6}
10^{4}
Fluence (protons−cm^{-2})
Feynman 2002
(35 years of data)
1963-1998
Event Fluence (cm^{-2})
Cumulative Probability of Occurence (%)
10 Largest
Observed Flares
Log-normal Model
Distribution
~68 flares in 7 years
Relative frequency
Log(Fluence)
0.01
0.1
1
5
10
20 30
50
70 80
90
95
99
99.9
99.99
Cumulative Probability
Top 10 largest observed flares, 1963−1991


IAASARS/NOA SREMHerschel : whole mission
10000.00
1000.00
100.00
10.00
1.00
0.10
0.01
protons cm^{-2}MeV^{-1}s^{-1}
0
500
1000
1500
Mission Days
12.6 MeV
18.2 MeV
26.3 MeV
38.0 MeV
55.0 MeV
79.5 MeV
115.0 MeV
166.3 MeV

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